Development of a multi-sphere artifact for evaluating gear-pitch-measuring instruments

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The degree to which the pitch measurement accuracy of a gear measuring instrument (GMI) can be calibrated on the sub-micrometer order is limited when using a gear artifact. A polygon mirror is high accurate index artifact; however, additional sensors, for example autocollimator, are necessary. It is difficult to construct the evaluation system on the factory field. In view of this situation, we propose a new method conducting GMI accuracy evaluation using a multi-sphere artifact whose spheres are treated as the teeth flank. The multi-sphere artifact is composed of equally spaced high-accuracy spheres around an axis. The tooth flank has waviness and roughness due to their complex geometrical profile. On the other hand, the sphere can be manufactured with an accuracy of several tens of nanometers; therefore, the measurement with extremely small uncertainty can be expected. The characteristics of the multi-sphere artifact are as follows: (i) The evaluation method of GMIs is user friendly, (ii) the measurement of GMIs is performed as in ordinary pitch measurement without any additional sensor. This paper describes how to evaluate the pitch measurement accuracy of GMI. We especially analyzed the setting error of the multi-sphere artifact on a GMI. We evaluated the pitch measurement accuracy of a GMI using the developed multi-sphere artifact. Finally, sub-micrometer evaluation was found to be possible.

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1. Introduction

The degree to which the pitch measurement accuracy of a gear measuring instrument (GMI) can be calibrated on the sub-micrometer order is limited when using a gear artifact. A polygon mirror is high accurate index artifact; however, additional sensors, for example autocollimator, are necessary. It is difficult to construct the evaluation system on the factory field. In view of this situation, we propose a new method conducting GMI accuracy evaluation using a multi-sphere artifact whose spheres are treated as the teeth flank. The tooth flank has waviness and roughness due to their complex geometrical profile. On the other hand, the sphere can be manufactured with an accuracy of several tens of nanometers; therefore, the measurement with extremely small uncertainty can be expected.

In this paper, we describe the characteristics of the developed multi-sphere artifact and the evaluation method of the pitch measurement accuracy of GMIs.

2. Multi-sphere Artifact

The multi-sphere artifact is composed of equally spaced high-accuracy spheres around an axis. Figure 1 shows a photograph of a manufactured multi-sphere artifact. The reference axis of multi-sphere artifact is perpendicular to the datum plane and passes through the center of reference band. There are two reference bands, which are called ‘centric reference band’ and ‘eccentric reference band’. The spheres are arranged around the reference axis which is defined by the centric reference band. The distance between two reference axes is 10 μm.

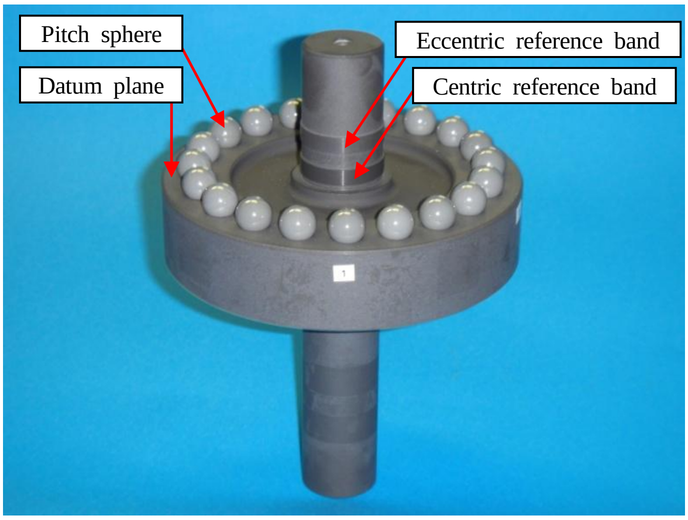

Fig. 1 Photograph of multi-sphere artifact

Table. 1 Dimensions of the virtual gear

Number of teeth	$z = 20$
Base circle radius [mm]	$r_b = 51.523$
Reference circle radius [mm]	$r = 54.837$
Normal pressure angle [deg]	$a_n = 20$
Normal module [mm]	$m_n = 5.484$
Tip circle radius [mm]	$r_a = 59.352$
Root circle radius [mm]	$r_f = 51.523$
Addendum modification coefficient	$x = 0.942$

Commercial GMIs can measure the pitch deviation of the developed multi-sphere artifact without any special software because a virtual gear dimension can be built for the multi-sphere artifact. Table 1 shows the virtual gear dimension. The determination of dimensions is reported in detail in the literature [1].

3. Evaluation of pitch measurement accuracy

The pitch measurement accuracy of GMIs is evaluated by comparing the calibrated pitch deviation. Concerning the difference between a measurement result and a calibrated pitch deviation, there are three main types of error components as follows:

(1) Calibration uncertainty
(2) Setting error component
(3) GMI error component

3.1 Calibration of multi-sphere artifact

We calibrated the multi-sphere artifact using a CMM (Leitz PMM866). Figure 2 shows a photograph of a measurement setup. The measurement value includes the systematic error of the CMM. We adapted as the multiple-orientation technique for reducing uncertainty components [2]. For the multiple orientation technique, the multi-sphere artifact was set up in different orientations around the reference axis. Figure 3 shows the calibrated result of the cumulative pitch deviation with respect to the reference axis which is defined by the centric reference band. The total cumulative pitch deviation for left flank and right flank were 5.9 μm and 5.0 μm. Figure 4 shows the calibrated result of the cumulative pitch deviation with respect to the reference axis which is defined by the eccentric reference band. The total cumulative pitch deviation for left flank and right flank were 21.2 μm and 20.9 μm. The measurement uncertainty (k = 2) of each calibration result was 0.2 μm.

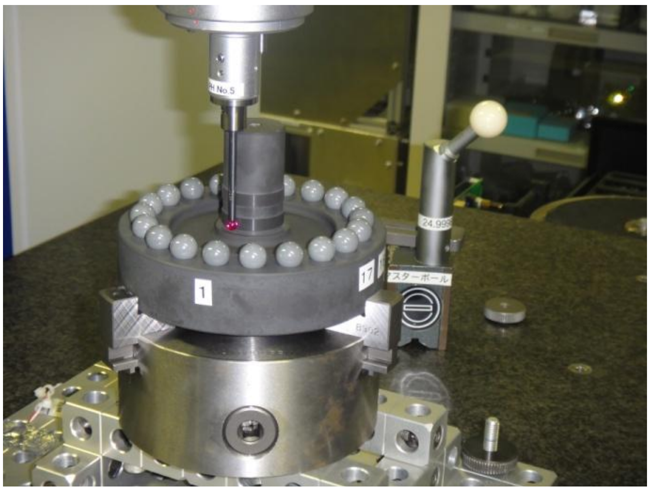

Fig. 2 Photograph of measurement setup on a CMM

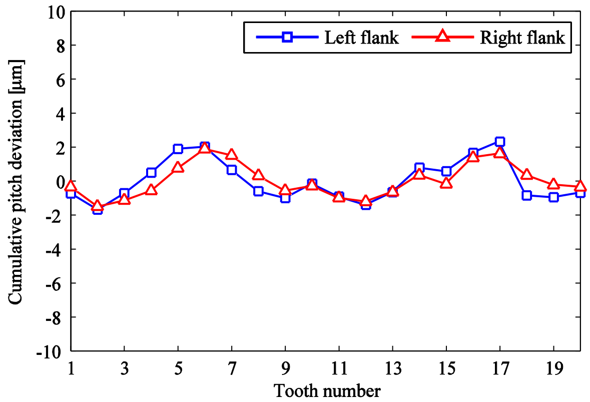

Fig. 3 Calibration result for cumulative pitch deviation. The reference axis is defined by the centric reference band

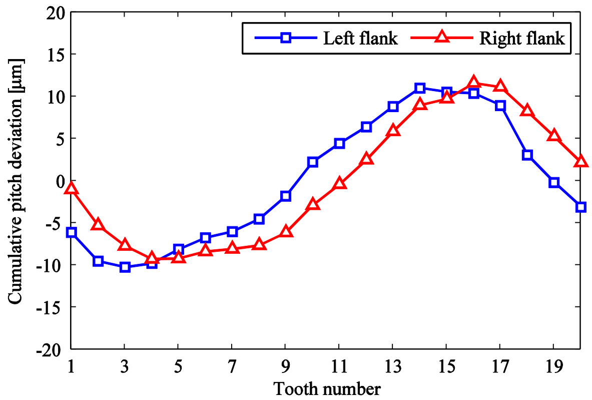

Fig. 4 Calibration result for cumulative pitch deviation. The reference axis is defined by the eccentric reference band

3.2 Setting error of multi-sphere artifact

The setting error of the multi-sphere artifact on a GMI is reflected in the evaluation result. The results of pitch deviation with respect to the different reference axis in figure 3 and 4 are a typical case. The degree to which the setting error affects the evaluation result will be discussed.

3.2.1 Inclination error

We discuss the change in an angular pitch deviation caused by an inclination error of the reference axis with respect to the GMI rotation axis. Figure 5 shows a schematic view of the change in angular pitch deviation. O-XY is the orthogonal coordinate system on a GMI and XY plane is the pitch measurement plane. We denote the maximum inclination angle of the datum plane with respect to the XY measurement plane by ω. When there is no inclination error, Point A and B are pitch measurement points on the reference circle. We denote the single angular pitch of ∠AOB by θ, where

$$\theta = 2\pi/z \tag{1}$$

When there is an inclination error, Point A' and B' are pitch measurement points on the reference circle. We denote the single angular pitch of ∠A'OB' by θ'. The change in the single angular pitch is calculated from the difference between θ and θ'. We denote the maximum value of the change in the single angular pitch by $\Delta\theta_{max}$ and it is calculated as

$$\Delta\theta_{max} \approx (1 - \cos\omega)\sin\theta. \tag{2}$$

Additionally, we denote the maximum value of the change in the cumulative angular pitch by $\Delta\Theta_{max}$ and it is calculated as

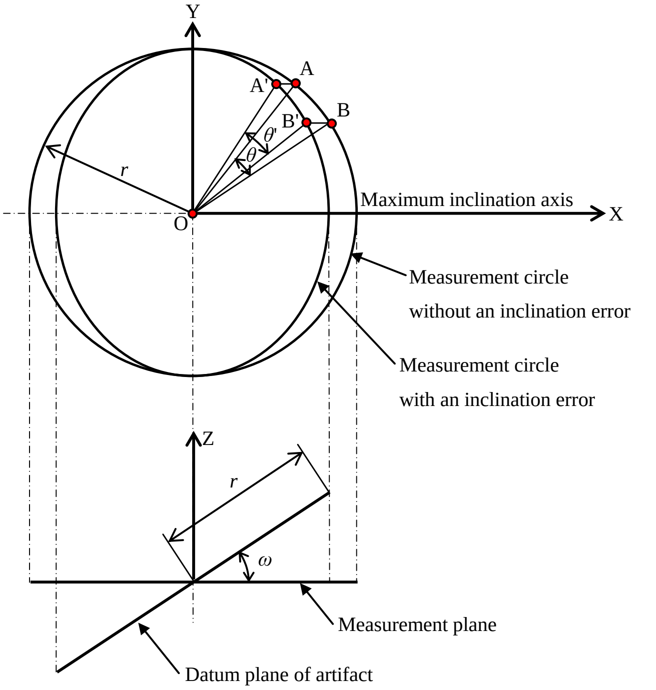

Fig. 5 Angular pitch deviation by an inclination error

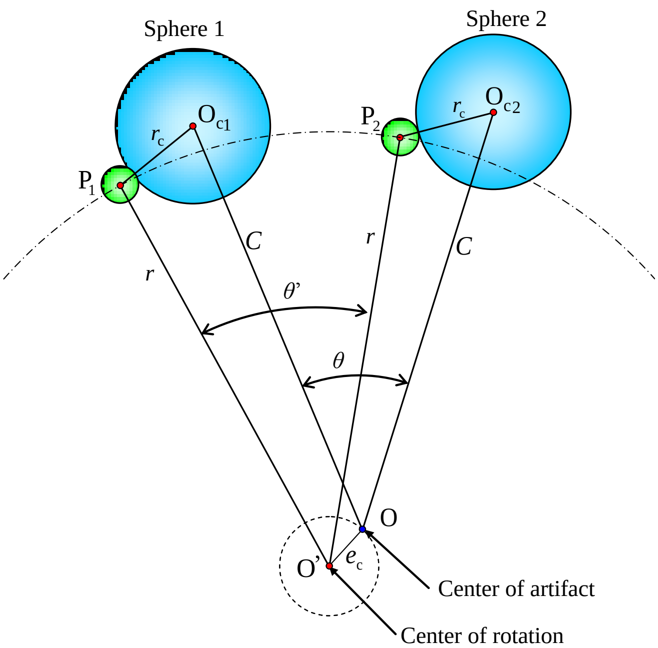

Fig. 6 Angular pitch deviation by an eccentric error

$$\Delta\Theta_{\max} \approx 1 - \cos\omega. \tag{3}$$

For example, when the maximum inclination error on the reference circle is 1 μm, the change in the single pitch deviation and the cumulative pitch deviation are 2.8×10^{-6} μm and 9.1×10^{-6} μm, respectively. It can be seen that the influence of inclination error is insensitivity.

3.2.2 Eccentricity error

We discuss the change in an angular pitch deviation caused by eccentricity error of the reference axis with respect to the GMI rotation axis. Figure 6 shows a schematic view of the change in angular pitch deviation. We denote the center of the multi-sphere artifact by O, the center of GMI rotation axis by O' and the eccentricity error by e_c. The change in the single angular pitch is calculated from the difference between θ and θ'. We denote the maximum value of the change in the single pitch deviation by $f_{\max}$ and it is calculated as

$$f_{\max} \approx \frac{2e_c \sin\left(\frac{\pi}{z}\right)}{\cos\alpha}. \tag{4}$$

Additionally, we denote the maximum value of the change in the cumulative pitch deviation by $F_{\max}$ and it is calculated as

$$F_{\max} \approx \frac{2e_c}{\cos\alpha}. \tag{5}$$

For example, when the eccentricity error is 1 μm, the maximum value of the single pitch deviation and the cumulative pitch deviation are 0.3 μm and 2.1 μm, respectively. Thus it was found from the foregoing results that the effect of setting error is dominated by the eccentricity error.

3.3 Evaluation of a GMI

'GMI error component' is the evaluation item. The pitch measurement accuracy of GMIs is evaluated by comparing the calibrated pitch deviations. The difference between the measurement value and the calibration value includes the setting error component. On the factory field, the setting error component at each measurement is different; therefore, it is necessary to evaluate the pitch measurement accuracy of GMI after dividing the GMI error component and the setting error component. The eccentricity component is expressed by the first Fourier component of the pitch deviation curve as shown Eqs. (4) and (5); thus, we evaluate the pitch measurement accuracy after eliminating the eccentricity error component from the measurement result. In this section, it is verified that the pitch measurement accuracy of a GMI can be evaluated by the measurement result with respect to the different reference axis.

Figure 7 shows a photograph of measurement setup. A GMI (Wenzel WGT350) was evaluated using the calibrated multi-sphere artifact. Table 2 shows the evaluation results. Figure 8 shows the measurement value and calibration value for left flank. Figure 9 shows the measurement value and calibration value for left flank after eliminating the eccentricity error component and figure10 shows the difference between its results. By eliminating the eccentricity error component, the measurement result with respect to the eccentric reference axis corresponds with the measurement result with respect to the center axis in calibration uncertainty order.

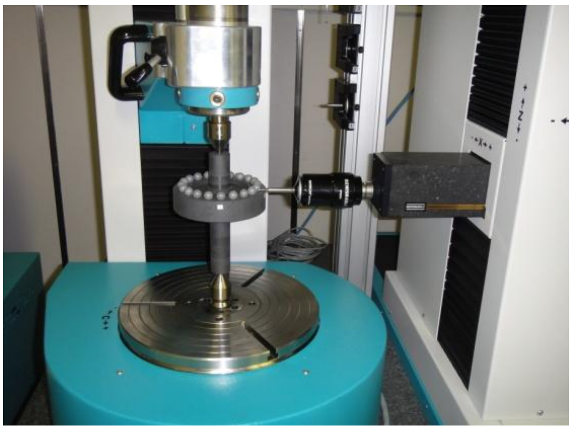

Fig. 7 Photograph of measurement setup on a GMI

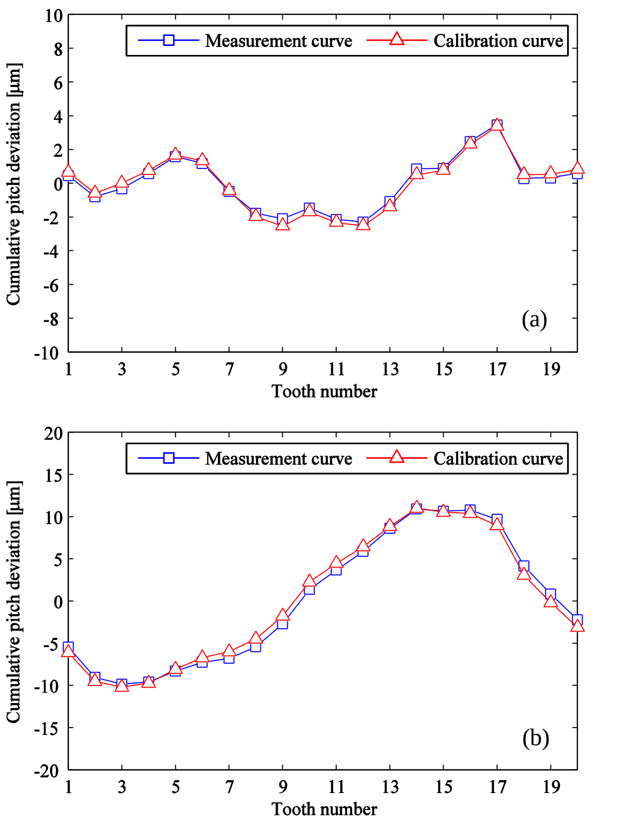

Fig. 8 Result of the measurement curve and calibration curve for left flank. (a) Reference axis is defined by the centric reference band and (b) reference axis is defined by the eccentric reference band

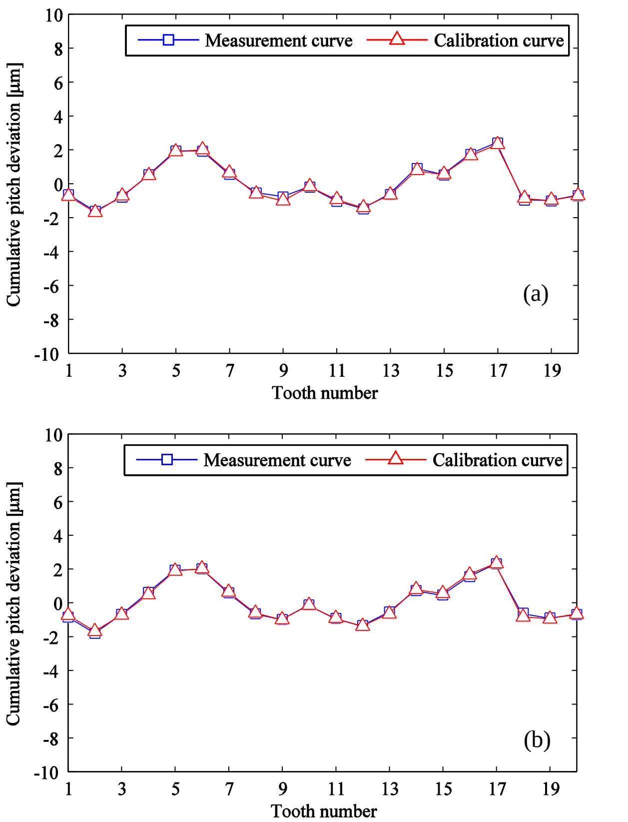

Fig. 9 Result of the measurement curve and calibration curve for left flank after eliminating the eccentric error component. (a) Reference axis is defined by the centric reference band and (b) reference axis is defined by the eccentric reference band

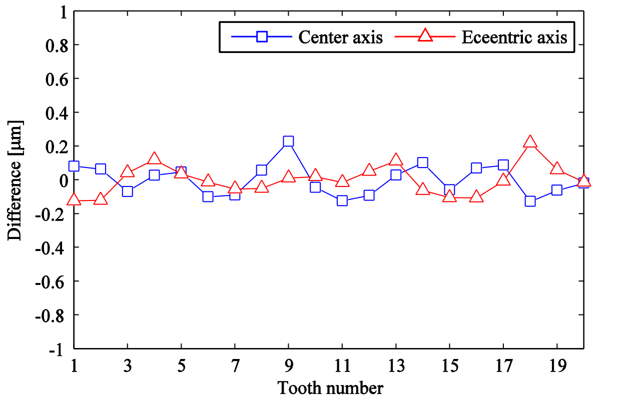

Fig. 10 Difference between the measurement curve and calibration curve for left flank after eliminating the eccentricity error component

Table. 2 Evaluation result. F_{pl} is the cumulative pitch deviation for left flank and F_{pr} is the cumulative pitch deviation for right flank. × is the result of which the eccentricity error component is not eliminated and ○ is the result of which the eccentricity error component is eliminated

Units: [μm]

		Center axis		Eccentric axis	
		GMI	Calibration value	GMI	Calibration value
F_{pl}	×	5.76	5.91	20.76	21.24
	○	4.03	4.01	4.05	4.00
F_{pr}	×	4.81	5.00	20.53	20.86
	○	3.60	3.39	3.45	3.39

4. Conclusion

A multi-sphere artifact was developed as a calibration artifact for evaluating the pitch measurement accuracy of GMIs. The characteristics of the multi-sphere artifact are (i) the spheres can be manufactured with an accuracy of several tens of nanometers and (ii) commercial GMIs can measure the pitch deviation of the developed multi-sphere artifact without any special software.

We proposed the evaluation method of pitch measurement accuracy using the calibrated multi-sphere artifact. We especially analyzed that the effect of setting error is dominated by the eccentricity error. It is verified that the pitch measurement accuracy of GMIs can be evaluated by eliminating the eccentricity error component.

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